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Research paper

Contribution of global GHG reduction pledges to bioenergy expansion

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ABSTRACT

With growing concerns about climate change, countries are increasing efforts to reduce dependency on fossil energy sources, the major source of CO_2, by replacing them with cleaner energy sources including bioenergy. In this context, the global bioenergy market has grown massively during the last few decades. In addition, under the aegis of the United Nations Framework Convention on Climate Change (UNFCCC) and the Paris Agreement, 162 countries have already submitted their intended nationally determined contributions (INDCs) to mitigate climate change, including greenhouse gas emissions pledges and action plans. Hence, the effect of these GHG restrictions on the bioenergy sector in the new expected global decarbonized energy system needs to be addressed. In this study, we estimate what role the international climate agreement could play in bioenergy sector expansion using the bottom-up energy system optimization model, TIAM-FR, a TIMES family model from ETSAP/IEA. As results, GHG restrictions promoted global bioenergy supply over the time horizon 2010–2050. In 2050, global biomass supply reaches 131–138 EJ under these climate scenarios, which is more than double biomass supply in the BAU scenario (60 EJ). In final bioenergy consumption, in 2050, only 3–5 EJ is consumed as biofuel in transport sector while 60 EJ of biomass is consumed for different uses in other sectors and more than 40% of total supplied biomass produces heat and electricity.

1. Introduction

The rapid economic development in emerging countries and the growing population have driven a sharp increase in fossil energy consumption and global GHG emissions. According to IEA statistics [1], the share of fossil energy in the global TPES (Total Primary Energy Supply), which refers to coal, gas, and oil products, was over 80% in 2011. The high consumption of fossil energy products during the last decades has accumulated CO_2 emissions in the atmosphere and brought about global warming. Concerns about climate change issues have encouraged countries around the world to mitigate GHG emissions together. At the 21st conference of parties (COP 21), held in Paris, France in December 2015, a new international climate agreement was signed to keep the global average temperature rise well below 2 °C above pre-industrial levels and to pursue efforts to limit the temperature increase even further to 1.5 °C. As of 22 August 2016, 162 parties have already communicated GHG emission reduction commitments to UNFCCC, including action plans until 2020 or 2030 [2]. The key solution to reduce GHG emissions and fossil energy dependencies is a diversification of the energy mix, but, during recent decades, the share of bioenergy in TPES has remained stable at 10%. However, the development of bioenergy transformation technologies has had a significant and more efficient impact on the bioenergy supply pattern. Between 1990 and 2011, the primary solid biomass supply including municipal and industrial waste dropped from 99.02% (37.6 EJ) to 93.37% (51.3 EJ) and was replaced by liquefied and gasified bioenergy sources such as ethanol, biodiesel, and biogas, whose share increased from 0.98% (400 PJ) to 6.63% (3.6 EJ) [1]. The phenomenon is particularly remarkable in the transport sector, where liquid biofuel consumption reached 2.45 EJ (7% of total gasoline and diesel consumption) in 2011 compared to 250 PJ (1.3% of total gasoline and diesel consumption) in 1990. These statistics indicate the transition from the use of traditional bioenergy with relatively low energy efficiency, for example, direct combustion of woods and crops, to modern bioenergy with increased energy efficiency, such as wood pellets, liquid and gasified biomass for electricity generation, transport fuels, etc. [3]. With the recent COP 21 decision to limit the global average temperature increase below 2 °C or 1.5 °C, the bioenergy sector is expected to expand further. In the IPCC SRREN (Special Report on Renewable Energy Sources and Climate Change Mitigation) [4], primary bioenergy supply reaches in the rage of

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25–300 EJ y^{-1} by 2050 for the tight climate mitigation scenarios (Cat.I+II: < 440 cm^3 m^{-3}) and 20–265 EJ y^{-1} for the less tight scenarios (Cat. III+ IV: 440–600 cm^3 m^{-3}). The GEA (Global Energy Assessment) scenario [5], which implies global CO_2 emissions reductions from energy and industry to 30–70% of 2000 levels by 2050, assesses 80–140 EJ of bioenergy supply by 2050. However, these studies did not imply climate mitigation scenario from INDCs. Only the recent version of WEO (World Energy Outlook)2016 from IEA analyzed potential deployment of bioenergy applying INDCs scenario. WEO 2016 projects 72 EJ y^{-1} of primary bioenergy supply by 2030 [6] with new policy scenario, which implies INDCs targets, and 96.7 EJ y^{-1} by 2040 with 2 °C scenario. Apart from WEO study, there are no other global studies that assess the relationship between bioenergy and current INDCs' GHG emissions reduction levels in an expected decarbonized energy system to explore different bioenergy pathways for the future. The aim of this paper is to discuss how the recent global GHG pledge will affect the bioenergy sector in a long term. This analysis is conducted with the global multiregional TIAM-FR optimization model, the French version of the TIMES Integrated Assessment Model developed under the Energy Technology Systems Analysis Program (ETSAP) of IEA. Our study involves the estimation of global bioenergy potential corresponding to the structure of TIAM-FR model.

The paper is organized as follows: Section 2 describes the methodology used for the analysis and the climate scenarios. Section 3 presents the model results for the longer term projection. The final section concludes with a discussion on the deployment potential of bioenergy.

2. Materials and methods

The evaluation of bioenergy avenues is performed through long-term scenario analysis for the period 2010–2050 with a bottom-up energy system optimization model, TIAM-FR, developed by the MINES ParisTech's Centre for Applied Mathematics [7]. Prior to the scenario analysis, we modified the current TIAM-FR structure, which comprised an aggregated level on biomass resources, and re-estimated the global bioenergy potential to correspond to the newly introduced structure. Secondly, we analyzed global GHG reduction scenarios based on INDCs communications and a 2 °C limit in the global temperature increase to observe the effects of GHG emission pledges on the bioenergy sector.

2.1. The TIMES integrated assessment model (TIAM-FR)

TIAM-FR is the French version of the world *TIMES Integrated Assessment model*, the global multiregional model from the TIMES family developed under the Energy Technology Systems Analysis Program (ETSAP) at the International Energy Agency (IEA) [8–10]. This model is based on a bottom-up approach and a technology-rich representation of the energy system to estimate how it will change and evolve in the long term. On the supply side, the reserves and resources of hard coal, lignite, conventional and unconventional oil and gas, including their supply costs, are presented for each world region. The energy conversion technologies for current and future energy systems, from extraction through primary energy supply and secondary energy supply to the end-uses, are detailed with technico-economic parameters. Regarding bioenergy conversion technologies, more than 100 technologies are integrated in TIAM-FR model over the entire regions and sectors. Summary of representative technologies are described in Appendix A.

On the demand side, 41 end-use demands (vehicle-km in the transport sector, tons of materials to produce in the industrial sector, lighting and water heating in the residential sector, etc.) for 5 energy-service sectors (agriculture, industry, commercial, residential, transport) are described based on socio-economic assumptions and on external projections of the growth of regional GDP, as well as population or the volume of various economic sectors over the entire time horizon (see Fig. 1 and Appendix B).

The model covers the time horizon from 2010 to 2050 divided into 5-year periods, and the world split into 15 global regions: Africa (AFR), Australia and New Zealand (AUS), Canada (CAN), China (includes Hong Kong, excludes Chinese Taipei; CHI), Central and South America (CSA), Eastern Europe (EEU), Former Soviet Union (includes the Baltic states; FSU), India (IND), Japan (JPN), Mexico (MEX), Middle-East (includes Turkey; MEA), Other Developing Asian Countries (includes Chinese Taipei and Pacific Islands; ODA), South Korea (SKO), United States of America (USA) and Western Europe (EU-15, Iceland, Malta, Norway and Switzerland; WEU). The regions are linked via the trading of energy and materials.

TIAM-FR is a linear programming model that aims to estimate an inter-temporal partial economic equilibrium on integrated energy markets assuming perfect markets and unlimited foresight over the time period, the described economic sectors and commodities [7]. The objective function is to minimize the discounted global energy system cost over the entire model horizon until 2050 under demand, environmental, and technological constraints. The net present value of the model is calculated based on (equation (1)) for each region.

$$NPV = \sum_{r=1}^{R} \sum_{y \in YEARS} (1 + d_{r,y})^{REFYR-y} \times ANNCOST_{r,y} \tag{1}$$

Where NPV is the net present value of the total cost for all regions over the calculation period; $ANNCOST_{r,y}$ is the total annual cost in region r and year y; $d_{r,y}$ is the discount rate; REFYR is the reference year for discounting; YEARS is the set of years and R is the set of regions (15 regions).

The results of the optimization are the structure of the energy system for each region, i.e. type and capacity of the energy technologies, energy consumption by fuel, development of emissions, energy trade flows between the regions and the resulting transport capacities required, and detailed energy system costs, plus information on the marginal costs of environmental measures, etc.

2.2. Bioenergy resource potential: methods

In the TIAM-FR model, biomass supply is characterized by manifold sources - bioenergy crops, solid biomass, industrial and municipal wastes, and land fill gas. Due to this aggregation level, current classification does not allow us to classify crop-specific or solid biomass types according to different technology progress or strategy/policy on biomass uses. We thus modified this structure by reformulating the extraction phase of biomass resources and the corresponding energy chain. In this study, we focus on bioenergy crops and solid biomass.

In the case of energy crops, which are aggregated into one commodity, the supply side was detailed based on a land-based approach due to possible land competition between different crops. In the literature, several studies have estimated global land availability for bioenergy production [11–17]. Overall, the estimated land availability varies depending on the approach, such as biomass flows and crop production, and on assumptions regarding land type, evolution of crop productivity, food demand projections, sustainability criteria such as water, and biodiversity issues. Furthermore, each study features a different geographical coverage, none of which comply with the TIAM-FR model. Hence, our study had to estimate its own bioenergy potential to implement into the

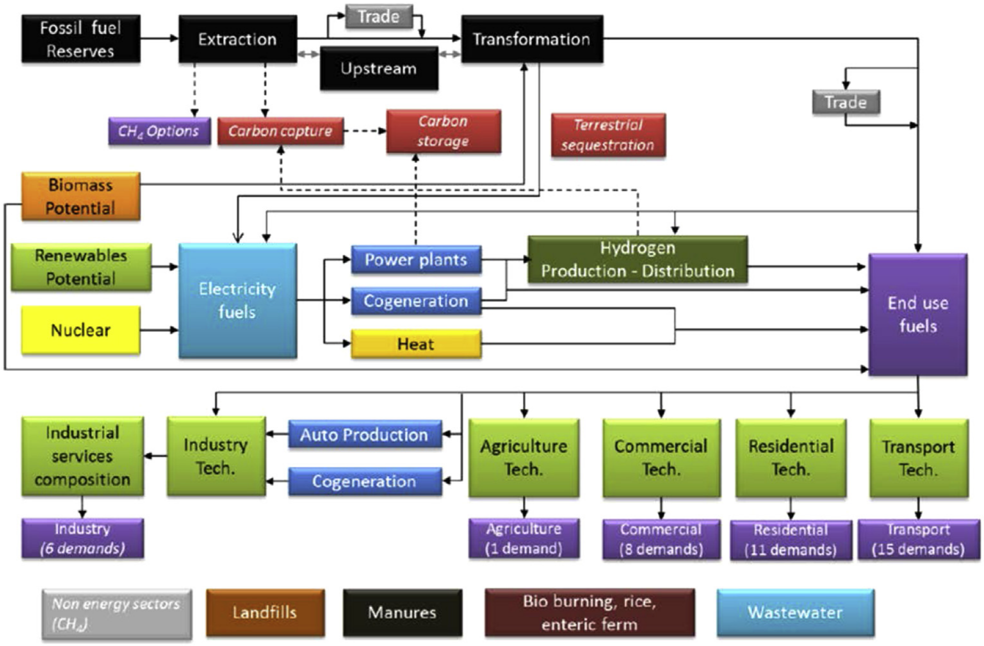

Fig. 1. Reference of energy system in TIAM-FR [8].

TIAM-FR model.

The land availability for each region was estimated based on a food-first approach. The concept of this methodology has previously been integrated into a study by Smeets et al. [11,12]. This approach makes food supply the priority of crop production in order to avoid potential food security issues, allowing only the remaining land to be used for energy crops.

The overall procedure applied in our study follows several steps. Firstly, future food demand is estimated based on future diet changes and demographic evolution. Future diet changes for each region, which include consumption of both crops and meat, are derived from the FAO projection on world agriculture [18]. The future diet data, which are expressed as commodity group consumption per capita, are broken down into different food commodities using current proportions presented in the FBS (food balance sheet) [19]. Then, demographic data from the United Nations population projection [20] are multiplied by future food consumption data to derive the final food demand for each region. Secondly, in addition to food crop demand, feed crop demand for livestock are also estimated based on feed conversion efficiency and feed composition for each animal product; both of these parameters were collected from the literature [11,21]. The final step in estimating food and feed demand is to convert these results into domestic productions using SSR (self-sufficiency ratio) expressed in equation (2).

$$SSR(\%) = \frac{production}{production + import - export} \times 100 \tag{2}$$

SSR is calculated and applied to each agricultural commodity and each region based on the FAO FBS (food balance sheet) at the TIAM-FR model reference year, 2010.

Concerning crop productivity, we applied the agro-climatically attainable yield for each crop and country taken from the GAEZ assessment to estimate land demands [22]. The projection of agro-climatically yields reflects climatic constraints such as temperature, radiation and moisture regimes. The GAEZ assessment also provides agro-ecological attainable yields that include soil fertility beyond climatic constraints. As our calculation applies soil nutrient quality to screen lands with low nutrient quality, agro-climatically attainable yields were used instead.

Lastly, we estimated future land availability for bioenergy production by extracting different types of land demand from “current cultivated land” and “grass and other wooded land” according to the land classification in the GAEZ assessment [22] and FAOSTAT [23]. We assumed no deforestation for bioenergy production for the sustainable criteria over the calculation period. This land estimation is described in equation (3).

$$\begin{aligned} Landavl_{r,y} = {} & Agr_{r,REFYR} + GRW_{r,REFYR} - Agr_{r,y} - Pasture_{r,y} \\ & - Builtup_{r,y} - Lowqual_r \end{aligned} \tag{3}$$

Where Landavl is the available land for region r, year y; Agr is land for agricultural production; GRW is grass and other wooded land; Pasture is land demand for grazing livestock; Builtup is land occupied by humans (infrastructure); Lowqual is land unsuitable for crop cultivation due to low nutrient quality of soil; REFYR is the reference year.

Within this land boundary, the soil nutrient level is used to filter out land unsuitable for crop cultivation. Also, built-up land demand is calculated by increasing the ratio of population density per country until 2050 [20] and the current built-up area per person. In the case of built-up area expansion in future, the additional areas are assigned to “grass and other wooded land” and “barren land”. Fig. 2 summarizes how the final available land for bioenergy production is derived.

To estimate forestry biomass, three sources of wood supply are taken into account: (1) Wood supply from forests, (2) Wood supply from other wooded land, and (3) wood supply from TOF (Trees Outside Forest). Wood supply potential from these sources is calculated based on natural forest growth (GAI: Gross Annual Increment) to respect sustainability of wood consumption for bioenergy purposes. The use of this indicator allows us to limit the exploitation of woody biomass to the natural growth level to preserve forest resources. Currently, no global statistics provide GAI data for each type of woody biomass source and each region/country, except for FAO, which publishes the NAI (net annual

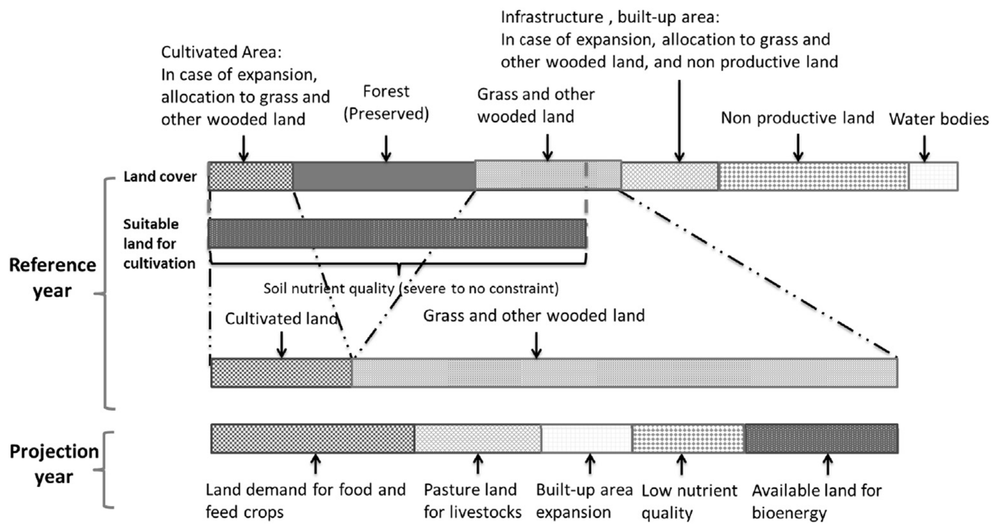

Fig. 2. Available land estimation summary.

increment) rather than the GAI (gross annual increment). Hence, we had to calculate the GAI for each region, which is differentiated in forests and other wooded land, using NAI, growing stock, forest surface, wood removal, and dead wood stock data [24,25]. Apart from wood supply from forests (1) and other wooded land (2), TOF (3) also provides significant woody biomass. However, the assessment of woody biomass potential from TOF still lacks data, and only a few countries carry out assessments. The recent version of FRA (Forest Resource Assessment) [24] recommends that the reporting countries include information on TOF. In addition, the FAO has evaluated TOF in 17 countries and defined TOF boundaries and methodology for assessment [26]. Based on these sources, we calculate wood supply potential from TOF for the different regions on which data are available.

Lastly, we calculate 3 types of agricultural and forestry residues (harvesting, logging residues and processing residues) using the residue generation ratio and recovery rate collected from a literature review [12,15,27–32]. Agricultural harvest residues are based on domestic production estimated previously for food supply. To estimate processing residues, we apply the quantity of food processed from each crop, which is derived from the proportion of the reference year's food processing in total consumption based on FAO FBS (food balance sheets). In the case of forestry residues, we take the residue generation ratio of 0.6 and 0.5 for logging and processing residues respectively and a recovery ratio of 0.75 for both logging and processing residues, collected from literature [11,12], and then multiply this figure by industrial roundwood consumption. Currently, region-specific data on wood demand projection are rarely available and, even when they are, the geographical coverage differs from TIAM-FR. From the literature review, the total global demand for industrial roundwood is normally projected in the range of 900 hm^3 (10 EJ) to 3100 hm^3 (36 EJ) [33–36]. These results are verified to correspond with a simple projection taking the level of current consumption per capita [34]. Hence, industrial roundwood demands are estimated to be 20 EJ by 2050 based on UN and FAO data regarding constant region-specific consumption per capita and demographic evolution. This result is in line with the other projections presented above.

2.3. Integration of bioenergy resource potential in TIAM-FR

The bioenergy potential for different biomass, for example, available surface for energy crop production, woody biomass potential, agricultural and forestry residues, was estimated as described in section 2.2 and integrated into the TIAM-FR model. Firstly, the available surface for bioenergy production is expected to reach about 24 Mm^2 by 2050 (Fig. 3) based on assumptions of 100% use of surplus agricultural land, 100% use of grass land except for animal production, and 20% of remaining wooded land.[1]

The results show that FSU, AFR, and North America (USA and CAN) are expected to have the largest available surfaces for energy crop production. Our estimation remains in the range of available surface area estimated in other studies, for example, 7.3 Mm^2 - 35.9 Mm^2 in Smeets et al. [11] and 4.3 Mm^2 - 31.8 Mm^2 in Hoogwijk et al. [15].

In TIAM-FR, available surface data is directly entered into each region at the extraction phases and associated with each crop yield for each region. In order to compare with other studies on bioenergy potential, generally expressed in possible energy units (EJ), our result is converted into energy potential using global average crops yields for bioenergy of 750–1260 tDM km^{-2} [13,37] and a gross calorific value of 18.3 MJ tDM^{-1} [30] (Table 1). As results, the global bioenergy potential from crops is estimated in the range of 333–559 EJ by 2050. This result is lower than in studies by Hoggwijk et al. [15] (8–1098 EJ) and Smeets et al. [11] (215 - 1272 EJ), but higher than in Erb et al. [16] (28–128 EJ) and WBGU (34–120 EJ) [13].

The difference between estimations mainly comes from several assumptions, such as projections of diet evolution, population, land use types, crop yields, heating values of crops, etc. The study by Hoggwijk et al. [14], which calculated available surface for bioenergy production using IPCC's climate scenarios (SRES) between 2050 and 2100, shows similar result to our study.

In the case of solid biomass potential, we assess agricultural and forestry residues for processing and harvesting and wood supply from forests, other wooded land and TOF, using the methodology described in section 2.2. To derive wood supply potential, the GAI index (gross annual increment) is calculated for both “forest” and “other wooded land”. The global average GAI is estimated to be about 191 m^3 km^{-2} y^{-1} for forests and 112 m^3 km^{-2} y^{-1} for other wooded land. This result is slightly below the GAI applied (210 m^3

[1] The rest of other wooded land was taken account to woody bioenergy potential estimation.

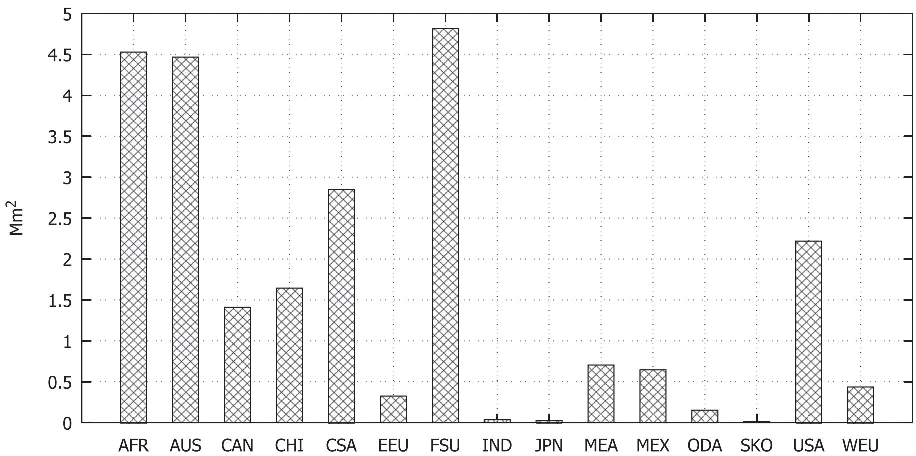

Fig. 3. Surface potential for bioenergy production by 2050.

Table 1
Comparison of energy crop potentials from literature.

Study	Regions	Time frame	Land use types	Potential
WBGU, 2008 [13]	Global	2050	Land suitable for bioenergy cultivation according to the crop functional types considering sustainability	34–120 EJy^{-1}
Smeets et al., 2007 [11]	Global	2050	Surplus agricultural land (100%)	215–1272 EJ y^{-1}
Hoggwijk et al., 2003 [15]	Global	2050	Surplus agricultural land, Surplus degraded land	8–1098 EJ y^{-1}
Hoggwijk et al., 2005 [14]	Global	2050 –2100	Abandoned agricultural land (100%) Remaining land not for other use (10–50%) Extensive grassland	311–657 EJ y^{-1}
Erb et al., 2009 [16]	Global	2050	Cropland not needed for other use intensification of grazing land	28–128 EJ y^{-1}
Our study	**Global**	**2050**	**Surplus agricultural land (100%)** **Surplus grassland (100%)** **Other wooded land (20%)**	**333–559 EJ** y^{-1}

[*] Adapted from IIASA [37] and modified by author.

km^{-2} y^{-1}) in the literature [11,12,34], which originally comes from the Global Fibre Supply Model (GFSM) [38].

The global solid biomass potential except for energy crops is expected to reach about 133 EJ y^{-1} by 2050 after extracting 20 EJ of industrial roundwood consumption (Table 2). Excluding 69 EJ of agricultural residue potential, only forestry biomass potential is evaluated as 64 EJ. In our study, note that fuelwood consumption is excluded from the forestry biomass potential; the TIAM-FR model treats fuelwood as an internal commodity, which becomes a choice of energy in an optimized energy system. By extracting fuelwood demands of 20–30 EJ [34], 34–44 EJ, our estimation of forestry biomass potential is comparable with other studies, for example, 42.5 EJ [34] and 12–74 EJ [39]. According to regional results, North America (USA, CAN about 15 EJ), the European Union (EEU, WEU, about 8 EJ), followed by AFR, CHI and IND, have the largest potentials of forestry biomass while AFR, CHI, IND, CSA, ODA (about 8 EJ for each region) have greater potential in terms of agricultural residues (Fig. 4).

Table 2
Summary of solid biomass potential by 2050.

Type	Potential (EJ $\mathbf{y}^{-1}$)
Sustainable wood supply	38
TOF supply	14
Wood Logging residues	3
Wood Processing residues	9
Agricultural harvest residues	57
Agricultural processing residues	12
Total	**133**

In order to provide biomass supply costs to TIAM-FR model, different methodologies and data from literature review were adopted [40–47]. Basic cost parameters are collected from IEA-ETSAP technology briefs [48], on which TIAM-FR model are based. For energy crops and forestry biomass, the evolution of production costs are estimated based on OECD-FAO Agricultural outlook [49] and FAOSTAT [19] coupled with the projected yield from GAEZ assessment as well as other studies [36,39,42]. For the rest of biomass commodities, regional labor costs from LABORSTA [50] and transport costs from ETSAP [48] were applied to the biomass production costs and regarding methodologies retrieved from the literature (see Appendix C).

2.4. Scenario development

In this study, three scenarios are explored. We begin by developing and calculating a business as usual (BAU) scenario. This baseline scenario with no emission constraints outlines some key patterns in the evolution of the energy system, and serves as the starting point for carrying out the analysis. The BAU scenario indicates that global GHG emissions will rise to 67.5 $GtCO_2$ eq by 2050, which is about 1.7 times higher than the 2010 GHG emission level (38.3 $GtCO_2$ eq).

The BAU scenario is compared to two GHG emission mitigation scenarios to investigate the implications for the future development of the bioenergy sector in the harmonized energy system between 2010 and 2050. These emission scenarios are developed at global level according to global GHG pledges (Table 3).

The first GHG mitigation scenario, hereafter called *Strict*,

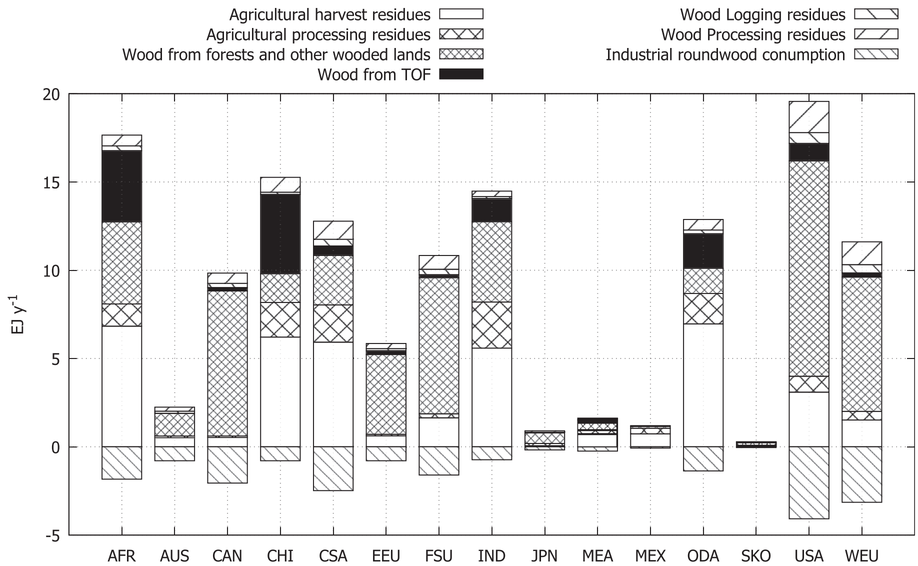

Fig. 4. Solid biomass potential by 2050 except for crops.

imposes a 50% reduction in global GHG (CO_2 eq) emissions by 2050 compared to 2010. This scenario is developed based on the IPCC's RCP2.6 scenario to maintain the global average temperature increase below 2 °C, which requires a reduction of 40%–70% in global GHG emissions by 2050 compared to 2010 [51]. In this scenario, a gradual reduction in global GHG emissions is applied over the period between 2010 and 2050.

The second GHG mitigation scenario, hereafter called *Moderate*, was developed based on INDCs' GHG reduction targets. According to the UNFCCC report [2], the implementation of GHG emission targets from all communicated INDCs reports will slow down the increase of global GHG emissions by 13% in 2025 and 16% in 2030 compared to 2010. This scenario does not impose the GHG emissions targets at a regional level, but at a global one. As the INDCs communicate GHG mitigation targets up to 2025, or 2030 for some countries, during the remaining periods from 2030 to 2050, 50% reduction in global GHG emissions by 2050 compared to 2010 is imposed. As results, this scenario limits GHG emissions to 43.3 GtCO_2 eq by 2025 and 44.4 GtCO_2 eq by 2030, and to 19.0 GtCO_2 eq by 2050.

3. Results

3.1. Total primary energy supply: bioenergy

Global primary energy supply in the BAU scenario increases from 344 EJ to 824 EJ between 2010 and 2050 with annual increase of 1.89% per year (Fig. 5). During this period, fossil energy dependency even increases from 310 EJ (80% of TPES) in 2010 to 697 EJ (85%) in 2050. By 2050, oil, gas, and coal account respectively for 28%, 19%, and 38% of TPES. Also, renewable energy with biomass and hydro increases by 161% (from 65 EJ in 2010 to 105 EJ in 2050). However, their share in TPES decreases from 17% to 13% by 2050 with increasing fossil energy consumption. In the case of biomass energy, consumption only goes up by 9 EJ, and its contribution to TPES drops to 7% by 2050 compared to 13% by 2010.

Table 3
GHG emissions scenario (Unit: GtCO_2 eq y^{-1}).

Year	*BAU*	*Strict*	*Moderate*
2010	38.3	38.3	38.3
2020	42.0	33.5	41.6
2025	–	31.1	43.3
2030	50.9	28.7	44.4
2040	58.8	23.9	31.8
2050	67.5	19.2	19.2

The GHG mitigation scenarios, *Moderate* and *Strict*, result in changes to this energy mix feature. The overall fossil energy supply drops noticeably, especially for coal, following the energy transition to low-carbon energy sources such as renewables, biomass, and nuclear.

GHG mitigation target presented in the *Moderate* scenario develops bioenergy and renewable energy supply by 7% and 9% by 2030, while decreasing fossil energy supply by 5% relative to BAU by 2030. Among the fossil energy sources, the share of coal supply in TPES, in 2030, decreases sharply from 36% to 25% relative to the BAU level, also in 2030. We observe lower demand for coal by 2030 in this scenario, replaced by gas, which increases from 19% to 25% compared to BAU in the same period. The oil consumption share remains at the same level of 30%. This GHG mitigation constraint cannot derive sufficient bioenergy development in terms of share of TPES, in which bioenergy contributes 9% in the BAU scenario by 2030 and 10% in the *Moderate* scenario.

However, during the post-INDCs period from 2030 to 2050, which aims to limit global GHG emissions to 50% of the 2010 level by 2050, the energy transition from fossil energy sources to low-carbon energy sources is accelerated. By 2050, the shares of renewable energy and biomass in TPES reach, respectively, 34% (286 EJ) and 16% (138 EJ). Relative to BAU level by 2050, biomass and renewable energy shares in TPES increase by 223% (229% in terms of demand) and 619% (636% in terms of demand). Moreover, the fossil energy share drops to 46% (*Moderate*) from 85% (BAU). The contributions of coal and oil to TPES decrease, respectively, from 38% to 2% and 27%–22% while the share of gas in TPES increases by 2 percentage point.

In the *Strict* scenario, which imposes a higher level of GHG mitigation than *Moderate* before 2050, the energy transition is observed earlier. In addition, in the same target year of 2030, with GHG pledges from INDCs, a similar pattern of energy mix change is identified but with greater intensity. By 2030, the *Strict* scenario increases biomass and renewable energy supply by 40% and 22%

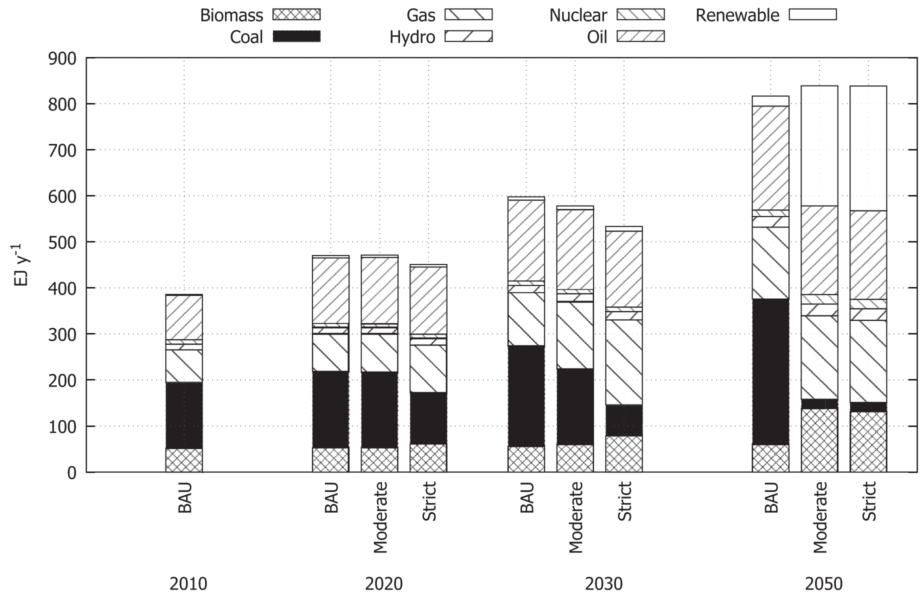

Fig. 5. Total primary energy supply under different scenarios (unit:EJ y^{-1}, "renewable" includes solar, wind, and other minor sources).

while decreasing fossil energy supply by 18%. The drop in the share of coal in TPES (from 36% to 28% for BAU and *Moderate* scenario to 12% for *Strict* scenario) and the replacement with gas (from 19% to 25% for BAU and *Moderate* scenario to 34% for *Strict* scenario) are also more intense. Both *Moderate* and *Strict* scenarios target the same level of GHG emission limit by 2050, and the energy mix of these two scenarios converges, but with a slight difference. The difference is due to the earlier investment in low-carbon energy sources. The total shares of biomass and renewable energies are similar, but the proportions are different in the two scenarios. In the *Strict* scenario, biomass and renewable energy contribute, respectively, 15% and 35%, compared to 16% and 34% in the *Moderate* scenario. Therefore, the results show that GHG mitigation targets have a positive impact on bioenergy development.

At the reference year of 2010, 51 EJ of biomass is supplied as primary energy (Fig. 6). In the BAU scenario, biomass supply increases relatively slowly compared to the GHG mitigation scenarios, *Moderate* and *Strict*. By 2030, biomass supply reaches 55 EJ under the BAU scenario, 60 EJ under the *Moderate* scenario, and 78 EJ under the *Strict* scenario. By 2050, the gap between the BAU scenario and the GHG mitigation scenarios widens, with 60 EJ for the BAU scenario, 138 EJ and 131 EJ for the *Moderate* and *Strict* scenarios. Over the time period, agricultural and forestry residues remain significant (71% of total biomass supply in 2010 and 58%–62% for *Moderate* and *Strict* scenarios). Demand for these sources steadily increases and exhausts available residues by 2040 in the *Strict* scenario and by 2050 in the *Moderate* scenario. With the increase in the residue supply, the BAU scenario reduces wood and energy crop supply over the entire period. On the contrary, GHG mitigation constraints augment the wood supply starting from 2020 in the *Strict* scenario and 2030 in the *Moderate* scenario. Similarly, energy crops become competitive from 2030 in the *Strict*

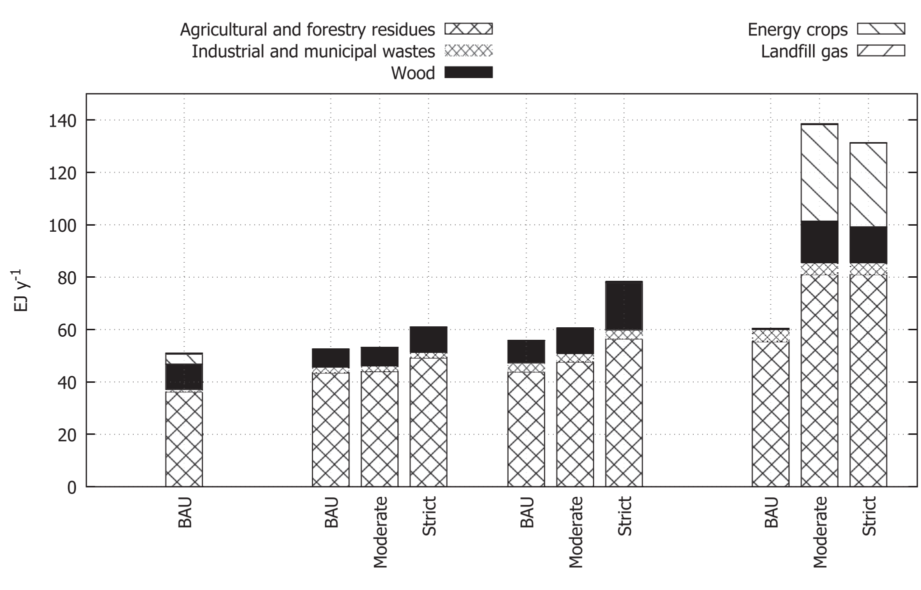

Fig. 6. Global bioenergy supply under different scenarios (unit:EJ y^{-1}).

scenario and 2040 in the *Moderate* scenario. Hence, in 2050 in the *Moderate* and *Strict* scenarios, respectively 11% (15 EJ) and 10% (13 EJ) of biomass supply come from wood and 26% (36 EJ) and 24% (32 EJ) from energy crops. Despite increased demand for these biomass sources due to GHG mitigation constraints, wood and energy crop availability is not saturated. The global surface for energy crop cultivation covers between 265 Mha and 334 Mha by 2050 under GHG mitigation scenarios.

3.2. Sectoral use of bioenergy

In final energy consumption, bioenergy is present in all sectors, i.e. agriculture, commerce, industry, residential and transport (Fig. 7).

In the BAU scenario, in 2050, the final consumption of biomass and biofuel reaches 7 EJ for industry, 34 EJ for residential, 0.9 EJ for agriculture, and 4 EJ for the transport sector. In GHG mitigation scenarios, the industrial sector exhibits the greatest change in final energy mix. In this sector, final coal consumption dramatically decreases to between 5.8 EJ and 5.9 EJ relative to 172 EJ in the BAU scenario by 2050, mostly replaced by solid biomass, heat and gas. Final consumption of solid biomass, heat and gas, in 2050, respectively reaches 10.6 EJ, 125–129 EJ and 33–36 EJ in the GHG mitigation scenarios. The residential sector is also influenced by GHG mitigation scenarios with an increase in solid biomass consumption to 40 EJ under GHG mitigation scenarios from 34 EJ under the BAU scenario in 2050. Solid biomass in the residential sector is generally consumed in improved wood stoves and cookers for heating and cooking. Concerning transport fuels, the *Moderate* and *Strict* scenarios derive biofuel consumption starting from 2030 to 2040 respectively. However, in 2050, the *Strict* scenario consumes less biofuel in the transport sector (about 3 EJ), compared to BAU (4 EJ) and *Moderate* (5 EJ). In this result, we identify similar phenomena to primary biomass supply. The stricter the GHG mitigation constraint, the earlier the investment on technologies. As a result, hydrogen vehicles are more developed than biofuels by 2050. Hence, hydrogen consumption reaches 38 EJ in the *Strict* scenario compared to 33 EJ in the BAU scenario.

In fact, GHG mitigation scenarios does not increase the total final bioenergy consumption (from 54 EJ in the BAU scenario to 62–64 EJ in GHG mitigation scenarios) but the power supply from biomass. In 2050, the power supply from biomass reaches 161 TWh in the BAU scenario, 5.087 PWh in the *Moderate* scenario, and 4.56 PWh in the *Strict* scenario (Fig. 8). Moreover, with a higher constraint on GHG mitigation, power generation from biomass with CCS technology starts growing from 2040. In 2050, biomass CCS technology dominates conventional power generation from biomass for the purpose of reducing GHG emissions (benefiting of negative emissions).

3.3. Contribution of bioenergy to climate mitigation

In this study, future pathways of bioenergy under climate mitigation policies were analyzed. Under TIAM-FR structure, it is difficult to estimate directly CO_2 marginal abatement costs of bioenergy uses. Hence, in order to reveal the role of bioenergy to climate mitigation, we compared global CO_2 marginal abatement costs under different configurations varying the input parameters as bioenergy potential and productivity of energy crops under *Strict* mitigation scenario. About 20% of the increase in productivity reduces land demand from 3.3 Mm^2 to 3.2 Mm^2 as well as CO_2 marginal abatement costs from 109 $ per tonne CO_2 to 102 $ per tonne CO_2 by 2050. On the other hand, about 10% of the decrease in productivity requires 3.5 Mm^2 of land for energy crops production and rises CO_2 marginal abatement costs to 113 $ per tonne CO_2. These results show that bioenergy is one of the important options to achieve climate mitigation target economically.

4. Discussion and conclusions

Faced with the goals of achieving energy independence and climate mitigation challenges, bioenergy receives an increasing attention. In this context, this paper discusses bioenergy potential and influence of GHG mitigation policies on future bioenergy pathways. As regards bioenergy potential, the land availability for energy crops production reaches 24 Mm^2 and solid biomass except for crops reaches 133 EJ of which 52 EJ from wood supply, 12 EJ from forestry residues and 69 EJ from agricultural residues, by 2050. Even though the high level of technical land availability, analyzed two climate scenarios demand only 2.7–3.3 Mm^2 of land for supplying 32–36 EJ of energy crops. These results can be compared to the IPCC AR5 (The Fifth Assessment Report) [52] which shows 25–35 EJ of energy crop potential by 2050 in "high agreement in literature".

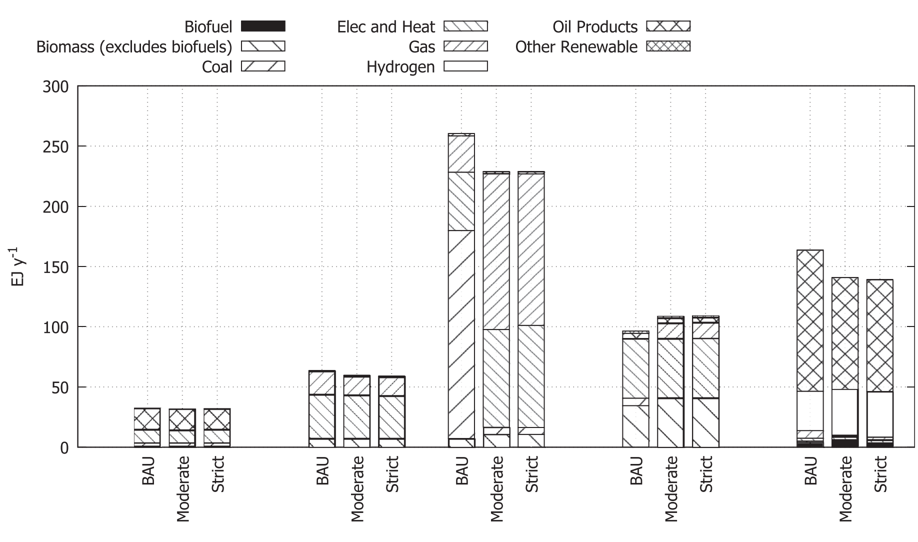

Fig. 7. Sectoral final energy consumption by 2050 (unit:EJ y^{-1}).

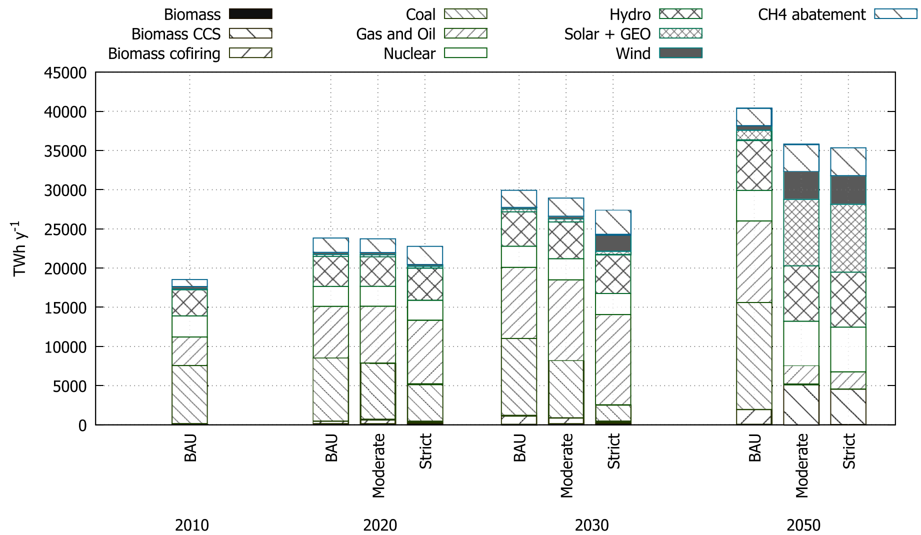

Fig. 8. Energy mix for electricity generation (unit: TWh y^{-1}).

Both GHG mitigation constraints promoted global bioenergy supply over the time horizon 2010–2050. In 2050, global biomass supply reaches 131–138 EJ under these climate scenarios, which is more than double biomass supply in the BAU scenario (60 EJ). In the case of final bioenergy consumption with GHG mitigation scenarios, in 2050, only 3–5 EJ is consumed as biofuel in transport sector while 60 EJ of biomass is consumed for different uses in other sectors and more than 40% of total supplied biomass produces heat and electricity (50–53 EJ). However, biofuel production and consumption start from 2030 in GHG mitigation scenarios and gradually increase to 2050 with the growing competitiveness of 2nd generation biofuels (ethanol from lignocellulosic, FT diesel). Other studies on the assessment of effectiveness among bioenergy uses concluded similar trends. In terms of GHG avoidance capacity and costs, biomass use for heat and power generation is globally evaluated more effective than biofuel consumption in the transport sector [40,53–55].

Despite the advantages of bioenergy as low carbon energy, several issues, such as LUC and iLUC (direct and indirect land use change), competition with food, water consumption, need to be addressed prior to further promotion of bioenergy [56]. In our estimation, the competition between food and bioenergy is taken account using a food-first approach. Land use changes to energy crops cultivation can directly impact on carbon storage capacity of soil, then, it can bring important variations in the global GHG balance [57,58]. For this reason, in our study, deforestation and land conversion of forests are prevented and conversion of other wooded land to energy crops cultivation is limited at 20%. Nevertheless, LUC/iLUC effect from current agricultural or grazing lands still require further research to be integrated in TIAM-FR model.

Moreover, the fresh water scarcity became a global issue and the interdependence between water and energy has received increasing attention. Water is used through the entire energy chain during mining, extraction, transformation, and transport. Especially, in the case of biomass, energy crops production requires significant volume of water. Several studies [59–61] showed that energy crops cultivation requires about 8–574 m^3 per GJ while conventional oil extraction requires 0.03–0.14 m^3 per GJ production. At this moment, bioenergy's impact on water resources is not introduced in the model and is a key issue of on-going research.

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Appendix A

Table A.1Summary of representative bioenergy conversion technologies in TIAM-FR

Bioenergy conversion technology	Conversion efficiency	CAPEX	O&M (% of CAPEX)
1st Gen. biofuels	33 - 76%	1.28–1.75 \$ $dm^{-3}y^{-1}$	5 - 6%
Advanced biofuels (Adv.Ligno-cellul. & BTL)	12 - 35%	1.7–2.5 \$ $dm^{-3}y^{-1}$	3–4.5%
Biomass Co-firing (Direct)	35 - 42% (44–85% with CHP)	430-550 \$ kW^{-1}	2.5–3.5%
Biomass Co-firing (Indirect)	33 - 42% (44–85% with CHP)	3000-4000 \$ kW^{-1}	5%
Biomass Co-firing (Parallel)	33 - 42% (44–85% CHP)	1600 - 2500 \$ kW^{-1}	4%

Appendix B

Regions	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
AFR	0,9133	1,0241	1,1429	1,2651	1,3879	1,5109	1,6335	1,7544	1,8711	1,9814
AUS	0,0245	0,0258	0,0271	0,0283	0,0295	0,0306	0,0316	0,0325	0,0333	0,0341
CAN	0,0323	0,0339	0,0355	0,0371	0,0387	0,0401	0,0414	0,0425	0,0435	0,0444
CHI	1,3191	1,3612	1,4034	1,4389	1,4611	1,4707	1,4707	1,4635	1,4488	1,4257
CSA	0,4467	0,4734	0,4983	0,5211	0,5414	0,5586	0,5726	0,5834	0,5911	0,5955
EEU	0,1191	0,1184	0,1176	0,1165	0,1150	0,1130	0,1106	0,1080	0,1053	0,1026
FSU	0,2848	0,2834	0,2832	0,2827	0,2810	0,2779	0,2743	0,2707	0,2669	0,2627
IND	1,1306	1,2145	1,2942	1,3672	1,4313	1,4846	1,5279	1,5648	1,5939	1,6138
JPN	0,1274	0,1270	0,1258	0,1237	0,1208	0,1174	0,1137	0,1098	0,1057	0,1017
MEA	0,2621	0,2871	0,3110	0,3345	0,3568	0,3773	0,3964	0,4137	0,4290	0,4417
MEX	0,1053	0,1106	0,1155	0,1197	0,1234	0,1265	0,1287	0,1299	0,1300	0,1290
ODA	0,9563	1,0298	1,1025	1,1720	1,2372	1,2974	1,3516	1,3993	1,4399	1,4728
SKO	0,0476	0,0485	0,0492	0,0495	0,0495	0,0491	0,0484	0,0473	0,0458	0,0441
USA	0,3027	0,3176	0,3323	0,3462	0,3587	0,3700	0,3800	0,3889	0,3968	0,4039
WEU	0,3991	0,4081	0,4143	0,4185	0,4212	0,4228	0,4235	0,4235	0,4227	0,4211
World	6,4711	6,8634	7,2526	7,6209	7,9535	8,2469	8,5049	8,7320	8,9238	9,0744

Figure B.1Population growth.

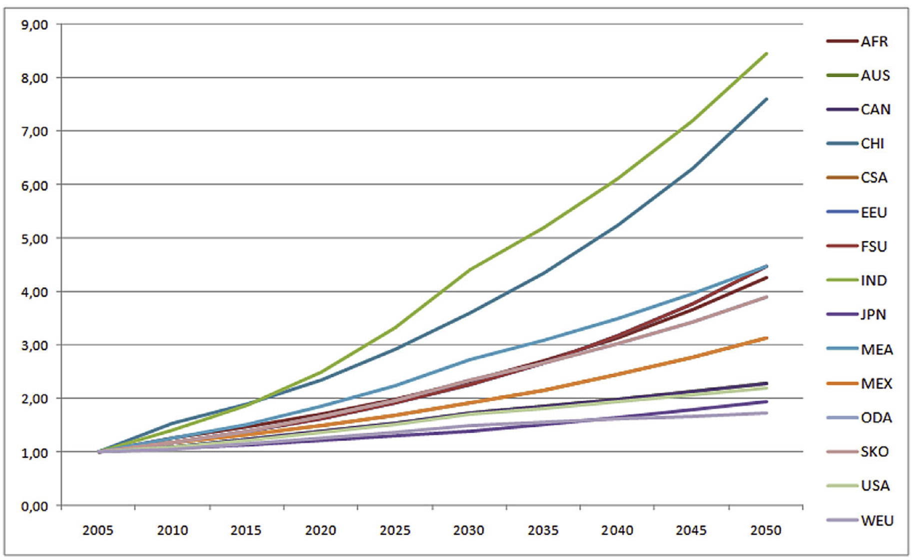

Figure B.2GDP evolution (multiplicator).

Appendix C

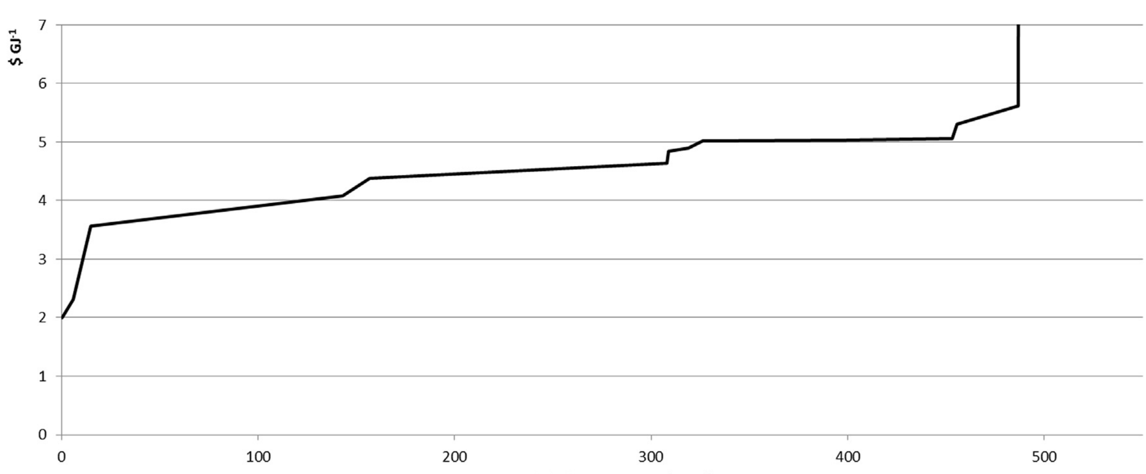

Figure C.1The cost supply curve of energy crops for the year 2050.

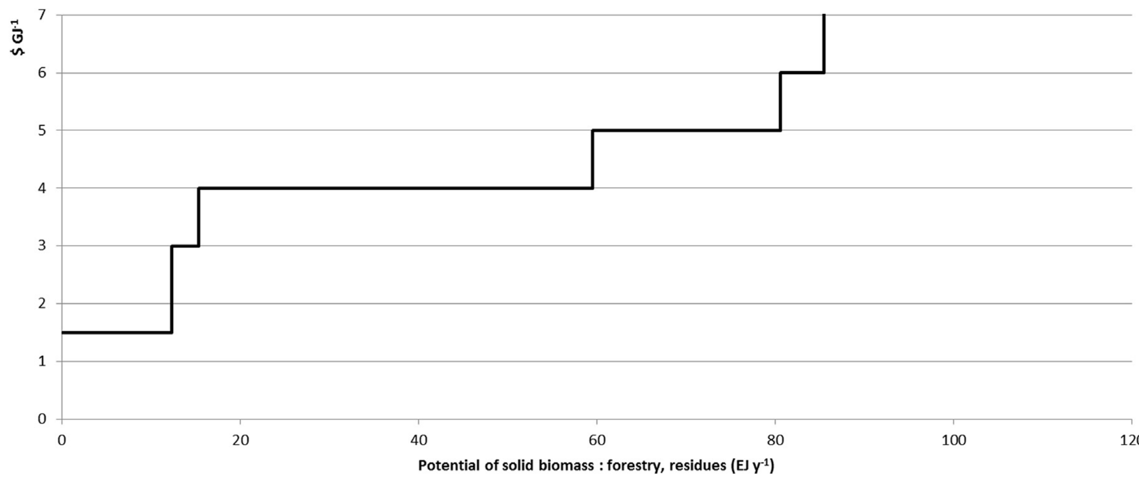

Figure C.2The cost supply curve of solid biomass for the year 2050.

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